ABSTRACT

SCHNEIDER, DOUGLAS GLENN. Structural and intensity changes in Hurricane Opal (1995) and Hurricane Fran (1996). (Under the direction of Lian Xie and Sethu Raman)

In this research, the processes that influence the structure and intensity of two Atlantic landfalling hurricanes are investigated. This is accomplished through an analysis of Hurricane Opal and Hurricane Fran. Hurricane Opal, which made landfall on the northern Gulf Coast of Florida, is used as a case study of trough interaction processes. As Opal approached land, it underwent a period of rapid intensification followed by a rapid weakening phase shortly before landfall. It is likely that Opal was strongly influenced by an upper level trough over the central United States. Initially, the trough seemed to aid in the rapid intensification of Opal through eddy momentum flux convergence and enhanced outflow aloft. Additionally, a warm core eddy in the Gulf of Mexico seemed to have an impact on the surface interactions of the hurricane. As Opal moved closer to the trough, the positive trough interaction processes appeared to be countered by the negative processes of vertical shear, PV displacement, and dry air intrusion at midlevels. This may have led to a change in the convective structure of the storm and as a result decreased the observed central pressure of Opal shortly before landfall.

The initiation of intense convection after landfall is investigated in Hurricane Fran. After Fran made landfall along the North Carolina coast, a convective cell formed and organized into a bow echo that crossed through the Raleigh-Durham area, causing unusually heavy wind damage up to 200km inland.

The mechanisms of formation and organization of this post-landfall convection are investigated. In addition, the characteristics of severe local storms that form in hurricanes are discussed. The processes that transformed the convective cell near the center of circulation into a bow echo that produced strong downbursts are also investigated. The results seem to indicate that the initiation of the cell shortly after landfall was caused primarily by an increase in surface friction, due to the resulting low-level convergence. This convergence enhanced the boundary layer radial inflow, which enhanced the vertical velocity. Large heat flux gradients resulting from bands of heavy rain in North Carolina in the days before Fran made landfall may have contributed to the enhancement of convection. As the cell moved across North Carolina, it began to organize into a bow echo. It was determined that the inflow of dry air at low to mid-levels of the troposphere may have been the primary mechanism in the organization of the cell into a bow echo. The rear inflow jet also provided dry, high momentum air that resulted in evaporative cooling and strong localized downbursts, which caused extensive damage to the Raleigh-Durham area.

BIOGRAPHY

Douglas Glenn Schneider was born on August 29, 1974 in Hackensack, New Jersey and is the son of David G. Schneider and Carol E. (Blanken) Schneider. He resided in Ridgewood, New Jersey for fifteen years and later moved to Sanford, North Carolina. He graduated high school from Lee County Senior High School in Sanford. The author has one older brother, David S. Schneider.

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STRUCTURAL AND INTENSITY CHANGES OF HURRICANE OPAL (1995) AND HURRICANE FRAN (1996)

by

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I. Introduction

A) PURPOSE AND OBJECTIVES

Accurate prediction of the track and intensity of landfalling Atlantic tropical cyclones is critical to the livelihood of millions of people who reside along the coasts of the Atlantic Ocean and the Gulf of Mexico in the United States. Rapid economic development in coastal areas has made billions of dollars worth of investments vulnerable to destruction by a landfalling hurricane (Sheets 1990, Marks et al 1998). People in these areas rely on forecasters to provide a timely and accurate prediction of the path and intensity of an approaching tropical cyclone. The best way for this to be accomplished is if the forecasters have a working knowledge of the most up-to-date research in the field of tropical cyclone forecasting.

The interaction of tropical cyclones with mid-latitude synoptic weather patterns has been recognized as an important factor in forecasting track and intensity changes in tropical cyclones (Marks et al. 1998). In order for an accurate forecast to be made, the forecaster must be aware of the processes of trough interaction with hurricanes. Changes in tropical cyclone track and intensity are dependent on numerous factors, not all of which are completely understood. While there is little debate that upper level mid-latitude troughs have a strong effect on tropical cyclone intensity changes, there is still some debate as to whether upper level troughs have a positive or negative effect on tropical cyclone intensity. Earlier studies into the effects of a trough in tropical cyclone intensity change focused on how upper level troughs can help to intensify the storm (positive trough interaction) through enhanced outflow. More recent studies have recognized the importance of upper level troughs in tropical cyclone weakening (negative trough interaction). The processes that determine whether a trough will help to intensify or weaken a tropical cyclone are current topics of intensive research. A thorough understanding of the interaction between synoptic troughs and tropical cyclones is necessary to provide the public with the most accurate forecast of tropical cyclone track and intensity as possible.

The forecasting of tropical cyclone intensity and structure after the storm makes landfall is also an important factor in public safety. The majority of research into tropical cyclone structure intensity focuses on changes before a tropical cyclone makes landfall. A limited number of studies have investigated the structural and intensity changes that a tropical cyclone experiences after making landfall (Powell 1987, Tuleya 1994, Willoughby and Black 1996).

As a hurricane makes landfall, it will experience changes in its thermodynamic and kinematic structure. While these changes typically result in a decrease of the overall intensity of the hurricane, they may lead to local increases in convection (Tuleya and Kurihara 1978). Friction can enhance the radial inflow, which can increase the low-level convergence and rising motions. The convective cells that form after landfall can be severe and can produce tornadoes or microbursts that add to the destructive force of the hurricane. The initiation of convection after a hurricane makes landfall is not an uncommon occurrence. Hurricane Andrew, which made landfall in southern Florida, experienced an increase in convection in the eyewall after it made landfall (Willoughby and Black 1996). Much of the damage in south Florida was attributed to the intense convection because of the observed damage patterns (Wakimoto and Black 1994). Strong precipitation-induced downdrafts brought high momentum air into the boundary layer, resulting in an acceleration of surface winds as the downdraft spread out horizontally (Willoughby and Black 1996). A convective cell that formed in Hurricane Fran caused an unusually large amount of wind damage to Raleigh, North Carolina, which is about 320 kilometers inland from the location of landfall. Radar observations show that this cell organized into a bow echo shortly before reaching Raleigh. The bow echo produced strong straight-line winds that were responsible for the extreme wind damage observed at inland areas.

The purpose of this thesis is to investigate the processes that affect the structure and intensity of landfalling hurricanes. The effect of upper level troughs on tropical cyclones is discussed, and processes that distinguish a positive trough interaction from a negative trough interaction are investigated. Previous studies that dealt with trough interaction with hurricanes are reviewed. Hurricane Opal is used as a case study of trough interaction processes in this research. The structure of hurricanes after making landfall is also examined. The initiation of intense convection after landfall is investigated in Hurricane Fran. The mechanisms of formation and organization of the convection are discussed, and characteristics of severe storms that form in hurricanes are investigated. The processes that led to the organization of the convective cell in Fran into a bow echo-type feature are investigated by reviewing studies about the formation of bow echoes. The initiation of downbursts in strong local storms is also discussed and investigated in Hurricane Fran.

B) ATLANTIC TROPICAL CYCLONE CHARACTERISTICS

Tropical cyclones are warm core mesoscale low pressure systems that form over warm tropical oceans. The primary energy source for a tropical cyclone is the release of latent heat. Studies have shown that the necessary processes for tropical cyclone generation and maintenance are conditional instability, mid-tropospheric moisture, absolute vorticity, weak vertical wind shear, upper level divergence, and a large body of warm water over a sufficient depth with sea surface temperatures greater than or equal to 26.5° C. Tropical cyclone formation is also dependent upon Coriolis force. The magnitude of Coriolis force is critical to the initiation of rotation. At very low latitudes, the Coriolis force becomes negligible. Therefore, these storms rarely form within the latitude belt between 5° S and 5° N. Coriolis effects play a key role in the generation of absolute vorticity, which is an important parameter in tropical cyclogenesis. The conditions listed above are most prevalent in the Atlantic Ocean from July through October with the peak of the Atlantic hurricane season in late August into early September. The average number of storms that reach hurricane intensity per year in the Atlantic basin is about six. Atlantic tropical cyclones are referred to as hurricanes when their maximum sustained winds reach or exceed 33 ms^{-1} (65 kts or 74 mph). Hurricane intensity is further classified by the Saffir-Simpson scale, which rates hurricane intensity on a scale of 1 to 5, with 5 being the most intense.

Changes in the track and intensity of a tropical cyclone are dependent on the environment that surrounds the cyclone as well as the structure of the cyclone itself. Mid-latitude upper level trough and ridge patterns can strongly affect a tropical cyclone's track and intensity. The movement of a tropical cyclone is determined primarily by the background mean flow of the environment, as well as the interaction of this mean flow with the internal dynamics of the tropical cyclone. The mean flow changes in conjunction with the synoptic patterns of high and low pressure systems. The synoptic patterns can also have a significant impact on the intensity change of a tropical cyclone. Trough and ridge patterns produce changes in upper level divergence, wind shear, moisture, stability, and vorticity, all of which are important ingredients in tropical cyclone maintenance. Variations in these synoptic scale parameters can cause changes in the mesoscale structure of a tropical cyclone. These processes will all impact the magnitude and distribution of the primary energy source for the storm, which is latent heat release. Whether a trough or ridge has a positive or negative effect on a tropical cyclone is dependent on numerous factors, not all of which are completely understood. This thesis will attempt to summarize these processes and analyze how these synoptic processes could have affected the track and intensity of Hurricane Opal (1995).

The influence of mesoscale processes on hurricane structure and intensity will also be discussed and analyzed. The mesoscale structure of a hurricane has been recognized as playing an important role in the storm's overall intensity. The predominant mesoscale feature of intense hurricanes is the eyewall, which is often a symmetrical ring of intense convection located in the center of the hurricane. The inner edge of the eyewall generally lies inside the radii of the maximum updraft, the maximum tangential wind, and the maximum low-level convergence (Cotton and Anthes 1989). The radial and tangential winds are important mechanisms in the maintenance of the eyewall. The outer region of the hurricane is dominated by bands of convection that are embedded in stratiform precipitation. Here, air flows radially inward toward the eye where it rises abruptly in the eyewall. Over an ocean surface, the inflow can provide warm, moist air to the inner core of the storm where large amounts of latent heat are released in the eyewall at mid-levels. After a hurricane makes landfall, the surface heat and moisture fluxes are reduced as the storm loses its oceanic heat and moisture source, which causes the overall intensity of the hurricane to be reduced. The counterclockwise surface tangential winds are strongly influenced by friction once a hurricane makes landfall. The increased surface friction slows down the winds, resulting in convergence, which can temporarily enhance rising motions. Changes in the convective pattern of Hurricane Fran (1996) had a significant impact on the severity of damage in certain locations of the storm after landfall. The processes that can initiate and organize convection in hurricanes after landfall will also be discussed.

C) HISTORY OF HURRICANE OPAL

Hurricane Opal was the fifteenth named storm and the ninth hurricane of the unusually active 1995 Atlantic hurricane season. Opal formed 130km south-southeast of Cozumel, Mexico on 28 September. The tropical depression tracked slowly to the north across the Yucatan Peninsula, then moved west into the Bay of Campeche where it developed into Tropical Storm Opal at 1200 UTC 30 September. Opal became classified as a hurricane at 1200 UTC 2 October and began to curve to the north-northeast. During this time, Opal intensified rapidly; the storm moved over a warm eddy with surface water temperatures of around 29°C and under a well-established upper level anticyclone over the Gulf of Mexico. The track of Opal and an infrared satellite image of the warm eddy is shown in Figure 1. The effect of the warm eddy was to increase the latent heat release in the inner core of the storm, and an upper level trough over the central United States provided an efficient outflow channel for the storm. The combination of these favorable conditions for intensification led to a drop in the central pressure of 16mb in 6 hours and 34mb in 12 hours. The minimum central pressure of 916mb was reached at 1000 UTC 4 October, and Opal was classified as a category 4 hurricane on the Saffir-Simpson scale. A plot of the change in central pressure with time is shown in Figure 2. Satellite imagery at this time showed the storm structure was nearly symmetric, and the storm contained a small, well-defined eye. The peak intensity occurred at the end of an eyewall contraction cycle as the inner eyewall began to dissipate. As it moved closer to the Gulf coast, the storm moved over an area of cooler sea surface temperatures. Opal began to fill rapidly as the central pressure increased to 942mb at the time of landfall. At 2200 UTC 4 October 1995, Hurricane Opal made landfall near Pensacola Beach, Florida. Around the time of landfall, an extra-tropical low pressure system and a deep upper level trough were situated over the central United States. The base of the upper level trough was located along the coast of Texas. A surface cold front was located to the west of Opal near the Mississippi River. The presence of the trough likely acted to increase the vertical shear to the western side of Opal. The same trough that may have enhanced the upper level outflow of Opal is also suspected to have caused the storm to weaken rapidly. While category 3 winds were reported along a narrow swath between Destin and Panama City, most of the Florida and Alabama coastline received category 1 to 2 winds.

D) HISTORY OF HURRICANE FRAN

Hurricane Fran formed off the Cape Verde islands in the Atlantic Ocean on August 23, 1996. Fran was the sixth named tropical cyclone of the 1996 Atlantic hurricane season. Fran moved west-northwest across the Atlantic Ocean in the wake of Hurricane Edouard, which had taken the same path a few days earlier. Once Fran moved away from the cooler waters left behind from Edouard, it intensified to a category 3 hurricane. It maintained its intensity as it approached the coast of North and South Carolina. Fran curved slightly to the northwest and made landfall at Cape Fear, North Carolina (New Hanover County). The minimum pressure attained by Fran during its lifetime was 946mb, and the central pressure at landfall was 954mb. Satellite images at landfall show that Fran developed an asymmetric structure after landfall. Figure 2 shows the track of Fran as it crossed North Carolina. It left a path of significant destruction as far inland as Durham, North Carolina. The amount of wind damage to the Raleigh area (Wake County) was unusual for an area so far inland. The damage in Wake and Johnston counties was equivalent to that caused by a F2 tornado. Damage estimates in North Carolina alone were about $2.5 billion. Radar observations reveal that an intense, non-tornadic convective cell formed in the hours after Fran made landfall. The cell intensified as it moved northwest, and its radar reflectivity pattern resembled a bow echo as it approached the Raleigh area. The intense convective cell may provide an explanation for the unusually heavy wind damage to the Raleigh area. The cell is suspected to have produced strong downbursts and straight-line winds that added to the destructive force of the hurricane. The formation, organization, and maintenance of the convective cell will be investigated in this thesis.

II. Intensity Changes and Trough Interaction Processes

A) LITERATURE REVIEW

1) Upper level outflow

Previous studies dealing with trough interactions have discussed how upper level troughs have a positive effect on hurricane intensity. Studies such as by Sadler (1976) have documented how the divergent flow on the eastern side of a trough can aid hurricane development and intensification by providing an enhanced outflow channel above the storm. Merrill (1988) described how the upper-tropospheric environmental flow affects the outflow layer structure of intensifying and nonintensifying hurricanes. The study described the environmental flow patterns that are conducive to tropical cyclone intensification. The pattern that was found to be most favorable for tropical cyclone intensification was one in which an upper level trough was located to the northwest of the tropical cyclone, which provides an efficient outflow channel for the storm. Rodgers et al. (1991) investigated how the outflow above a tropical cyclone can initiate or intensify the convection in the storm. Increased outflow above a tropical cyclone will aid in strengthening the storm by mass continuity. As air is removed from the top of the storm by divergence, air from below must rise to replace it, resulting in increased rising motions in the inner core of the storm. This will increase the latent heat release in the eyewall of the storm, which will in turn lower the central pressure of the storm and increase the wind speeds. While an upper level trough can enhance the outflow of a tropical cyclone, vertical shear from the trough can negatively affect the storm.

2) Relative angular eddy momentum fluxes

More recent studies, such as those by Molinari and Vollaro (1989) and DeMaria et al. (1993), have discussed trough interactions that led to intensification through fluxes of relative eddy angular momentum. Because of the strong pressure gradient between a hurricane and its environment, there will be an increase in the mid-level inflow and upper level outflow of the hurricane. The resulting increase of momentum that is experienced by the hurricane will result in an increase in its overall intensity. The momentum flux is often strongest in cases where a hurricane is approaching an upper level trough. DeMaria et al. (1993) demonstrated that the negative effect of vertical shear by the trough can begin to dominate over the positive effects of eddy momentum flux as a tropical cyclone approaches the trough axis. The study analyzed 32 named storms from 1989 to 1991 and found that enhanced eddy flux convergence within 1500km of the storm center due to the interaction with an upper level trough had a strong positive effect on tropical cyclone intensity. However, in many of the cases observed by DeMaria et al. (1993), vertical shear or decreased SST eventually led to a decrease in tropical cyclone intensity. The study concluded that the same synoptic features that caused the enhanced eddy flux convergence also increased the vertical shear, resulting in a decrease in storm intensity in several cases. A study by Kaplan et al. (1997) compared the relative importance of eddy momentum to vertical shear in three Atlantic hurricanes. Preliminary results of the study show that Hurricane Bertha (1996) experienced an increase in intensity before landfall due to increased momentum flux despite encountering increased shear. Hurricane Edouard (1996) and Hurricane Hugo (1989) both intensified rapidly in a low-shear environment without the benefit of increased eddy momentum fluxes (Kaplan et al. 1997).

3) Potential vorticity

Potential vorticity (PV) has been recognized as an important parameter in determining the effects of an upper level trough on tropical cyclone track and intensity. Potential vorticity is proportional to the product of the absolute vorticity and the static stability,

$$PV = -(\zeta + f)\frac{\partial \theta}{\partial p}$$

Regions of highest potential vorticity occur where the vorticity and static stability are high. In hurricanes, this region most often occurs in the upper levels of the storm, while low PV or a negative anomaly often occurs at low levels where static stability are lower. A study by Molinari et al. (1995) documented the importance of potential vorticity on hurricane intensification. The study determined that the intensification of Hurricane Elena was caused primarily by the interaction of the storm with an upper level trough and its associated positive potential vorticity anomaly. The study described how a potential vorticity anomaly can either weaken or enhance the outflow anticyclone, depending on the relative strength of the negative PV anomaly at low levels of the storm center. The study found that the upper level outflow of a storm can be enhanced by a positive PV anomaly aloft if the low level negative PV anomaly in the hurricane is adequately strong. The study also mentioned that if a positive PV anomaly is strong enough relative to the negative PV in the center of the storm, it can act to weaken the upper level anticyclone. This will reduce the outflow above the storm, which will reduce the storm's intensity.

4) Vertical shear

The vertical shear associated with troughs has been recognized as having a strong negative effect on hurricane intensity. The impact of PV advection and vertical shear were compared by Hanley (1997), who hypothesized that the positive effect of PV advection dominated the negative effect of vertical shear in Hurricane Bertha. DeMaria (1996) used a 2-D nonlinear balance model to demonstrate that the effect of vertical shear was to alter the thermal structure of the vortex by differential PV advection. According to that study, the effect of vertical shear is to tilt the positive PV anomaly, which will result in mid-level warming in the vortex center. This will result in increased stability and decreased convection in the storm center, and the storm will likely weaken. A limited number of studies have attempted to determine the dynamical processes that distinguish positive from negative trough interactions, and questions remain about the relative importance of each of the processes in tropical cyclone intensity changes.

B) APPLICATIONS TO HURRICANE OPAL

1) The Rapid Intensification of Opal

Between 2200 UTC October 3 and 1000 UTC October 4, the central pressure of Hurricane Opal dropped from 950mb to 916mb. The rapid intensification can be attributed to several factors. A Gulf of Mexico warm core eddy was located in the central Gulf of Mexico, directly in the path of Opal. This warm core eddy can be seen in the AVHRR satellite image of water surface temperature in figure 1. Opal crossed the eddy between 0600 UTC 4 October 1995 and 1200 UTC 4 October 1995, which is also near the time of Opal's greatest rate of intensification. A study by Shay et al. (1998) calculated the heat content of the warm core eddy. It was likely that the presence of this warm core eddy was an important mechanism in supplying the hurricane with strong surface heat fluxes that helped intensify the storm. An upper level trough located several hundred kilometers to the northwest of Opal may also have contributed to the storm’s rapid intensification. An analysis of satellite-derived upper level winds by Bosart et al. (1998) found that there was a significant increase in upper level divergence near Opal before the storm's rapid intensification. Several features were found in the analysis that contributed to the rapid intensification of Opal, including strong outflow channels to the northeast and southeast of Opal and a large scale trough to the northwest. The combination of the strong upper level divergence and an efficient outflow channel to the northeast and southwest of Opal enhanced convection by increasing the mid-level ascent, which aided the rapid intensification. Studies such as Sadler (1976) have shown that rapid intensification of a tropical cyclone occurs when an upper level trough is located to the west and poleward of the storm. This effect can be attributed to eddy angular momentum fluxes and enhanced upper level divergence. However, as described by DeMaria (1996), the trough that provided these positive factors for intensification can also provide negative factors for intensification, primarily by increasing vertical shear. A similar situation occurred with Hurricane Opal. The upper level trough to the northwest of Opal may have initially aided in the intensification of the storm through enhanced outflow and eddy momentum fluxes. However, as the storm moved closer to the trough, the vertical shear increased, which appears to have played an important role in the weakening of the storm before landfall. The same upper level trough that played a role in the rapid intensification of Opal also may have aided in weakening Opal before landfall. The change in surface heat flux as Opal moved away from the warm core eddy also contributed to the rapid weakening of the storm. The study by Shay et al. (1998) found that the oceanic heat content near the northern coast of the Gulf of Mexico was 9 to 10 times lower than the heat content of the warm core eddy. When Opal moved away from the warm core eddy at around 1200 UTC 4 October 1995, the central pressure began to fall rapidly. The loss of the diabatic heat source seems to have been the initial mechanism that reduced the intensity of Opal.

2) Structural characteristics of Opal

The base of an upper level trough was located in western Louisiana around the time of landfall, and an upper level jet was located at the base of the trough. An infrared satellite image at 2159 UTC 4 October 1995 (Figure 4) shows that Opal had a very asymmetric cloud pattern as it made landfall. Nearly all of the convective activity in the hurricane is located on the northern and eastern sides of the storm. There is virtually no cloud cover on the western side of the storm, and the southern side is beginning to dry out. After landfall, the cloud cover on the southern side of the storm was virtually eliminated due to dry air being entrained into the circulation. The western side of Opal was being strongly sheared by the presence of the upper level trough. A series of satellite images show a progressively asymmetric structure of the storm due to increasing shear as the storm moved closer to the upper level trough. An analysis of 300mb dewpoints (Figure 5) was performed using model initialization data from the North Carolina State University's Mesoscale Atmospheric Simulation System (MASS) model. The zonal domain of the MASS model is a 45 km grid and is initialized with the 0000 UTC Operational Eta run, as well as rawinsonde, surface, buoy, and satellite data. The figure shows very dry air stretching from Pennsylvania to the Louisiana coast. The dry air is intruding into the western side of Opal, resulting in the reduced cloud cover on that side of the storm. The narrow area very dry air at this level that parallels the Mississippi River seems to be caused by subsidence on the cyclonic side of the outflow jet from Opal

(Shi et al. 1990). Because of the counterclockwise primary circulation of Opal, the dry air is being wrapped around to the southern side of the storm middle and lower levels. The inner core convection of Opal began to decrease as the storm moves closer to land and to the upper level trough axis. Rodgers et al. (1991) observed a decrease in convective activity when an upper-tropospheric trough was positioned close to or over a tropical cyclone. This was caused by a weakening in the storm outflow and the entrainment of dry upper-tropospheric air into the inner core of the storm. After making landfall, the entire backside of Opal was completely precipitation-free, as the dry intrusion eliminated any significant cloud cover behind the storm.

The advection of dry air from the west seemed to aid in the rapid intensity decrease of Opal as the storm approached land. Opal had undergone a rapid deepening phase about 15 hours before making landfall. Shortly after intensifying, Opal weakened nearly as quickly, as the central pressure rose from 916mb to 942mb in about 12 hours. The reduction of diabatic surface forcing as Opal moved away from the warm eddy around 1200 UTC 4 October was probably the first mechanism that began the rapid weakening of the storm. The dry air intrusion may have played an increasingly important role in the decay of Opal as it approached land. As is evident in the visible satellite image at 2159 UTC (Figure 4), Opal lacked a well-defined eye. The absence of an eye is indicative of a weakening hurricane, as stated by Willoughby et al. (1984). The entrainment of dry air into the mid-level circulation of the storm reduced the moisture and subsequent latent heat release aloft in the hurricane core. This mid-level dry air intrusion most likely caused the inner eyewall to quickly decay and reduced the overall intensity of the storm. This physical process has been described previously by Powell (1987). The study described how middle and upper level cooling was an important mechanism in weakening a hurricane as it approached land. The entrainment of dry air into the storm's circulation along with the reduction of diabatic surface forcing as Opal moved away from the Gulf of Mexico warm eddy were probably important factors in the early stages of the observed rapid weakening of Opal prior to landfall.

A secondary wind maximum was observed to have formed behind Opal's primary rainband (Powell and Houston, 1997). The wind maximum formed as the hurricane underwent an eyewall contraction cycle. This cycle took place as Opal began to rapidly decrease in intensity. The contraction cycle is evident in satellite images, which show that Opal lost its distinct eye in the hours before making landfall. Secondary wind maxima that contract to the center of the hurricane have been associated with intensifying storms. Opal's maximum intensity occurred at the end of an eyewall contraction cycle. Although Opal contained a secondary wind maximum about 100km from the storm center, the wind maximum did not contract once Opal began to weaken. Secondary wind maxima contract to the center of a hurricane because of differential adiabatic warming resulting from increased diabatic heating near an inertial stability gradient (Molinari et al. 1995). In Hurricane Opal, the diabatic heat release in the storm's core was being reduced, which would act to prevent the wind maximum from contracting. The reduction in diabatic heat release was most likely due to the storm encountering relatively cooler water and to the entrainment of dry air from the western side of the storm into the inner core region. The outer wind maximum remained around 100km from the storm's center as it made landfall. A reduction of diabatic heat release at mid-levels in the storm’s inner core seemed to be an important factor in the rapid deintensification of Opal prior to making landfall.

3) Potential vorticity and vertical shear

Patterns of potential vorticity can also affect the convective patterns of tropical cyclones. Vertical shear can cause the upper level positive potential vorticity anomaly to become displaced from the low-level negative anomaly. This will cause the thermodynamic and mass fields to adjust, which will change the patterns of vertical motion. This process of displacing the upper level PV anomaly by vertical shear can bring about asymmetries in the structure of a hurricane, which may lead to weakening of the storm. An analysis of potential vorticity was performed using initialization data from the MASS model. Figure 6 is a cross section of potential vorticity anomaly as Opal makes landfall. In the figure, an area of relatively high PV was located to the west of Opal. This positive PV anomaly was associated with the upper level trough. A weak negative PV anomaly was located at the low levels of Opal. Molinari et al. (1995) described how patterns of PV can affect the outflow anticyclone above a hurricane, hence changing the storm’s intensity. The study described how a low level negative PV anomaly in Hurricane Elena (1985) prevented vertical shear from having a negative affect on the hurricane's intensity by strengthening the outflow anticyclone, with induced synoptic scale wave breaking. Hurricane Elena formed in the Gulf of Mexico and tracked northward on a similar path as Opal. Elena intensified rapidly as it approached land, as an upper level trough was located to the northwest. Strong inner core convection in Elena resulted in a strong negative PV anomaly at low levels. This strengthened the outflow antcyclone caused the approaching upper level trough to become tilted with respect to a north-south plane, which reduced the vertical penetration depth and duration over with vertical shear was able to influence the hurricane (Molinari et al. 1995). This process most likely played an important role in the observed rapid filling cycle of Hurricane Opal, except in a reverse fashion. Around 1000 UTC 4 October, Opal was located over a Gulf of Mexico warm core eddy with an average SST of about 29°C. Opal then encountered cooler water of about 26°C and began to weaken. The movement of Opal away from a warm core eddy in conjunction with the intrusion of dry air into the inner core of the storm may have led to a decrease in the static instability in the inner core of the storm. According to the equation of PV, an increase in the static stability will lead to an increase in PV. A reduction in static instability acted to weaken the low-level negative PV anomaly in the center of the storm, which in turn may have acted to weaken the upper level outflow anticyclone by reducing inner core convection. Since a relatively strong positive PV anomaly from a trough encountered the hurricane, the vertical shear from the trough was able to negatively affect the storm over a greater depth and duration because of the weakened upper level anticyclone. If the negative PV anomaly had been sufficiently strong relative to the approaching positive PV anomaly, effect of vertical shear may not have been as significant. According to Molinari et al. (1995), a tropical cyclone over warm water with strong inner core convection will have a strong outflow anticyclone, which can help induce synoptic-scale wave breaking, which reduces the scale of the trough and reduces the negative effect of vertical shear.

Figure 7 shows a cross section of shear, calculated from the MASS model data, shortly before Opal made landfall. The highest values of shear are located to the west of Opal. According to DeMaria (1996), the effect of vertical shear is to tilt the positive PV anomaly, which will result in mid-level warming downwind near the vortex center. This will result in increased stability downwind and decreased convection near the storm center, and as a result the storm is more likely to weaken. The displacement of the upper level PV anomaly by the vertical shear will cause asymmetries in the convective patterns of a hurricane, which will also aid in weakening the storm. The dry intrusion into the core of Opal that likely reduced the convection in the inner core of the storm, the reduced potential energy available from the ocean, and the asymmetric convective pattern were probably the important physical mechanisms that were initially responsible for reducing the hurricane's convection. These processes likely acted in conjunction to weaken the storm's overall outflow characteristics and as a result increased the likelihood of vertical shear-induced tropical cyclone weakening as described by DeMaria (1996).

III. Structural Changes in Hurricanes After Landfall

A) LITERATURE REVIEW

1) Increased convection after landfall

Powell (1987) described the low-level kinematic and thermodynamic structure of Hurricane Alicia as it made landfall near Galveston, Texas in 1983. The study showed how the wind field and temperature field in Alicia changed from and underlying ocean surface to an underlying land surface. The effects of increased friction and reduced moisture availability on the storm's intensity was described. Although the central pressure of Hurricane Alicia was rising rapidly after landfall, hurricane-force winds were maintained six hours after landfall, causing significant damage in downtown Houston. Powell suggests that active eyewall convection provided the momentum to support strong winds. An analysis of the wind field in the study found that asymmetries in the perturbation wind field were produced partially by the land-sea frictional difference. The perturbation wind field was obtained by subtracting the axisymmetric mean surface circulation from the surface wind field. An anticyclonic flow was produced over land, while a cyclonic flow was produced just offshore. The anticyclonic perturbation flow over land opposed the mean cyclonic flow of the vortex. This acted to increase the low-level convergence over land. The convergence enhanced the boundary layer radial inflow, which enhanced the upward motion. Several tornadoes were spawned in rainbands in the northeast quadrant of the hurricane where surface convergence was strongest.

A numerical simulation of a landfalling tropical cyclone by Tuleya and Kurihara (1978) found that the increased friction that a tropical cyclone encounters as it makes landfall can lead to enhanced rising motions while the overall intensity of the cyclone will decrease. Their simulations showed that the effect of increased friction is to decrease the horizontal wind speed and increase the cross-isobar angle of the wind toward low pressure. The enhanced inflow increases the mass convergence, which increases the rising motion. Increased moisture convergence temporarily increases the precipitation, but the lack of heat and moisture over land eventually leads to a reduction in middle and upper level diabatic heating. This results in cooling in the middle and upper levels and a decrease in the overall intensity of the simulated hurricane. The advection of cool, dry air into the mid-levels of the storm can also decrease its intensity through the same process.

A study of the sensitivity of a landfalling hurricane to soil thermal properties, bulk subsurface layer temperature, land wetness, and surface roughness was performed by Tuleya (1994) using the Geophysical Fluid Dynamics Laboratory (GFDL) tropical cyclone model. A disturbance was allowed to develop over an ocean domain, then was translated over a land domain to determine the effects of landfall on a fully developed tropical cyclone. When the land surface temperature was explicitly predicted by the model, a rapid decrease of intensity occurred, regardless of the wetness of roughness of the surface. However, when the land surface temperature was held equal to the ocean temperature (302°K), the disturbance maintained its intensity, despite the increased roughness and decreased moisture (Tuleya 1994). The study concluded that the decrease in surface temperature at landfall has a greater effect on tropical cyclone weakening than the decrease in surface moisture and the increase in surface friction.

2) Characteristics of severe storms in hurricanes

McCaul and Weisman (1996) simulated a shallow supercell thunderstorm in a landfalling hurricane. The study compared the characteristics of supercells in hurricanes with those that form in the midwest United States. The storm environment in hurricanes is characterized by strong shear, low CAPE (convective available potential energy), and high moisture. The lapse rate in hurricanes is near moist adiabatic. This results in storms that are shallow and more intense at low levels because buoyancy is confined to low levels. In midwest supercells, the updraft speed is greatest in the upper troposphere because the buoyancy is greatest at that level. The peak updraft velocity for the simulated midwest supercell is typically located around 5km while the peak updraft velocity for a typical hurricane supercell is around 1.5km (McCaul and Weisman 1996). However, the low level updraft speeds in hurricane supercells can equal or exceed the updraft speeds of a typical midwest supercell thunderstorm. This is due to the strong perturbation pressure gradient force that forms from strong low level shear in hurricanes.

The updraft dynamics of a convective storm are determined by the vertical velocity acceleration:

$$\frac{dw}{dt} = B - C_p \theta_0 \frac{\partial \Pi'}{\partial z}$$

where C_p is the heat capacity of air at constant temperature and θ_0 is the base state potential temperature. The updraft acceleration is driven by the buoyancy force, ***B***, which arises primarily from the release of latent heat, and vertical gradients in perturbation pressure, expressed here in terms of the nondimensional perturbation Exner function. The perturbation pressure acceleration can be divided into components of dynamically driven accelerations (Π'_d) and vertical buoyancy gradients of Π'_b by taking the divergence of the inviscid momentum equation, giving:

$$-\nabla \cdot (\rho_0 V \cdot \nabla V) = C_p \nabla \cdot (\rho_0 \theta_0 \nabla \Pi'_d)$$

$$\frac{\partial \rho_0 B}{\partial z} = C_p \nabla \cdot (\rho_0 \theta_0 \nabla \Pi'_b)$$

where ***V*** is the velocity vector and ρ_0 is the mean density profile (Houze 1993). Vertical gradients in buoyancy and gradients in acceleration lead to local perturbations in pressure that drive the updraft. Vertical cross sections of vertical velocity acceleration, perturbation pressure gradient force, and buoyancy force were compared for simulations of a typical midwest supercell and a typical hurricane supercell in the study. In the case of the midwest supercell, the contribution of buoyancy force to updraft velocity dominates in the middle and upper levels of the storm. In the hurricane supercells, the dynamic pressure perturbation force dominates updraft behavior over the buoyancy force because of the strong pressure forcing associated with low level momentum deflection (McCaul and Weisman 1996). The low-level momentum deflection can be caused by increased friction as a hurricane makes landfall. The contribution of buoyancy force in updraft acceleration is less in hurricanes than in typical midwest supercells due to the lower CAPE in the hurricane environment. In the hurricane supercell simulated by McCaul and Weisman (1996), the upward dynamic pressure gradient force contributed three times as much to updraft speed as buoyancy.

Tornado formation in hurricane supercells differs slightly from midwest supercells. Tilting and stretching of horizontal vorticity by the strong low level updrafts produces vertical vorticity in supercells. Horizontal vorticity is generated by gradients in buoyancy, which are caused by surface cold pools. In hurricanes, surface cold pools tend to be weak. This prevents strong surface vorticity development, which may explain why tornadoes in hurricanes tend to be weaker than tornadoes in the midwest. Several studies have observed shallow tornadic storms in environments with low CAPE but strong shear (Davies 1990, Kennedy et al. 1993, Stalker et al. 1993). Similarities between these cases and hurricane tornadic storms include high relative humidities throughout the troposphere and little or no capping inversion. These storms are usually forecast poorly because of the unusually low CAPE. A study by McCaul (1991) collected sounding data from landfalling hurricanes that produced tornadoes to form a composite sounding for a typical tornadic-hurricane environment. The temperature profile of the composite sounding was conditionally unstable below 650mb and stable above. High relative humidities dominated throughout the troposphere with dewpoint depressions less than 6ºC. The hodograph showed winds veering with height and strong vertical shear in the lowest 1km. The level of the strongest winds was around 2 to 3 km. While the study found that the CAPE value in the composite hurricane that was 10% lower than the CAPE values of typical midwest tornadic storms, the bulk Richardson number of the hurricane sounding fell into the "possible supercell" category because of the strong low level shear.

3) Downburst and bow echo dynamics

Caracena and Maier (1987) analyzed a microburst from an observational network in southern Florida. The study determined the characteristics of a microburst in a humid environment. Observations revealed that the mircoburst-producing storm was characterized by an elongated, rapidly propagating echo. The study proposes that the cell formed because of strong boundary layer convergence aligned parallel to the cell motion. A mid-level dry layer was also observed with the cell. Evaporative cooling was found to be a more important mechanism in producing the microburst than water loading by one order of magnitude. The microburst occurred when the cell had matured, and the cell began to dissipate shortly thereafter because of the cool outflow that undercut the cell (Caracena and Maier 1987).

Johns and Hirt (1987) summarized the characteristics of a derecho, or a convectively induced windstorm. Derechoes can cause as much destruction as a tornado through damaging outflow winds resulting from multiple downbursts. The radar signature of a derecho can be described as a short, curved squall line that is oriented perpendicular to the mean wind direction. The study by Johns and Hirt (1987) determined the important parameters in derecho formation to be convective instability, relative humidity, and lower to mid-tropospheric wind speeds. The development of a derecho is aided by strong winds and low humidity in the mid-troposphere. The intensity of the outflow from a derecho was found to be dependent on the negative buoyancy created by evaporation and the vertical transport of high momentum air aloft to the boundary layer.

The evolution and structure of a bow echo and its associated microbursts was studied by Lee et al. (1992). The study stated that a bow echo forms from the redistribution of hydrometeors by a vorticity couplet. This vorticity couplet forms due to the interaction of vertical shear with a downdraft. The couplets form on the tips of the elongated echo, which results in the protrusion of the echo in the direction of cell motion. A rear inflow jet can also be an important factor in bow echo formation, according to the study. The transport of dry air by the rear inflow jet can erode the echo by subsidence and evaporation (Lee et al. 1992). The increased evaporation can enhance the negative buoyancy in the cell, which will strengthen the downdraft. The rear inflow jet is also a source of high momentum air aloft which can be transported into the boundary layer, thereby creating stronger downdrafts and possibly microbursts.

B) APPLICATIONS TO HURRICANE FRAN

1) Radar observations

An analysis of Doppler radar data from the KRAX radar (located near the Wake County and Johnston County line) was completed using WATADS version 9.0 from the National Severe Storms Laboratory. At 0112 UTC 6 September 1996, approximately one hour after landfall, a wind maximum was located about 80km to the north of the eye. The radial velocity of the wind maximum was measured by the KRAX Doppler radar at $55 ms^{-1}$ at about 2.5 km above the ground. A 0024 UTC surface wind analysis by the Hurricane Research Division of NOAA/AOML found a wind maximum of $45 ms^{-1}$ that was located to the northeast of the eyewall. The southern portion of the eyewall decayed quickly after the storm made landfall, and at 0326 UTC a cell measured at 55 dBZ developed in Duplin County on the northwest side of the remaining eyewall (Figure 8). A vertical cross section of radial velocity from the radar through the wind maximum on the north side of the remaining eye shows that a radial wind maximum was located between 2.5km and 3km above the ground (Figure 9). In the figure, values of radial velocity are strongly aliased. The actual radial velocity values were found by using the formula

$$V_{true} = 2\,V_{Nyquist} \pm V_{measured}$$

where V_{true} is the actual radial velocity, $V_{Nyquist}$ is the Nyquist velocity or the maximum radial velocity that can be measured before aliasing occurs, and $V_{measured}$ is the radial velocity that is measured by the radar and is shown in the figure. In Figure 9, the radial velocity of the wind maximum at 2.5km is shown as 3ms^{-1} inbound relative to the position of the radar. The Nyquist velocity is 26ms^{-1}, so the true radial velocity is 55ms^{-1}. The cell intensified to 60 dBZ before weakening to 52 dBZ at 0523 UTC. By 0534 UTC, the cell reorganized into a horseshoe shape and intensified to 56 dbZ in Johnston County (Figure 10). A vertical cross section of radial velocity at 0558 UTC (Figure 11) reveals that the radial wind maximum weakened to 53 ms^{-1} and descended to about 1km above the ground. A vertical cross section of reflectivity in Figure 12 shows the dry air being brought into the rear of the cell. The region of maximum wind begins at 2km and descends to below 1 km. This descent of the dry air helped to enhance the evaporation in the cell, which contributed to the production of strong downdrafts. As the cell continued to the northwest, it intensified to 62 dBZ and became elongated at 0615 UTC (Figure 13). The wind maximum behind the cell continued to descend to about 0.5 km. This descending rear inflow jet brought dry, high momentum air into the boundary layer, which added to the destructive force of the straight-line winds. At 0638 UTC, the reflectivity pattern of the cell has taken on a distinct bow echo pattern (Figure 14). The cell maintained its bow echo shape until about 0713 UTC when it began to weaken and become disorganized. The cell then began to take a more northerly track into Granville County and weakened to 53 dBZ.

The radar estimated 3-hour precipitation is shown in Figure 15. While radar estimates of precipitation are typically underestimated in tropical cyclones, this data is useful to locate the region of maximum precipitation and the maximum intensity of the cell. The intensification of the cell is also evident in the figure as precipitation reaches a maximum at the Wake and Johnston County border, which is the location of the cell's greatest intensity. The maximum values of the 3-hour precipitation estimates are around 2 inches. A local study conducted by the National Weather Service Forecast Office in Raleigh found that doubling the radar estimated amount of precipitation provided a close value to the actual observed precipitation for a tropical system. This would bring the precipitation amount from the cell in the Raleigh area to about 4 inches. Observed rainfall amounts in eastern Wake County for September 6 were around 7 inches. The single convective cell, which passed through Wake and Johnston counties in less than three hours, accounted for more than half of the total precipitation produced by Fran in those counties.

2) Precipitation analysis

Precipitation data from September 2 to September 6, 1996 were collected from over 90 data recording stations. These stations included cooperative observer sties, National Weather Service sites, and North Carolina Agricultural Network recording stations in eastern and central North Carolina, northern South Carolina, and southern

Virginia. The data were plotted using the General Meteorological Package (GEMPAK), and a Barnes objective analysis was performed on the irregularly spaced data. The Barnes scheme is a two-pass, successive correction scheme that assigns weight to a datum according to the distance between the datum and a grid point according to a Gausssian function. Figure 16a shows the results of the objective analysis of rainfall on September 2 through 4, and Figure 16b shows the objective analysis of rainfall on September 5 and 6 that was produced by Hurricane Fran. While the objective analysis should not be relied upon to obtain actual surface rainfall values due to the data filtering and extrapolation processes, it is useful to determine patterns of rainfall and areas of minimum and maximum rainfall.

The precipitation that was produced on September 2 through 4 was analyzed to determine if surface moisture gradients were present to create differential surface heat fluxes that may have contributed to the development and maintenance of the convective cell that formed after landfall. Figure 16a is an objective analysis of rainfall data collected in Virginia, North Carolina, and South Carolina in the days preceding Fran. Rainfall totals in the region were quite high as some areas received more rainfall before Fran than during Fran. The areas that received the most precipitation were the coastal region (counties adjacent to the coast) and the Central Piedmont (from Johnston County westward) with a minimum of precipitation located between them in the Coastal Plain. As the cell moved into this area of minimum antecedent precipitation, it experienced a rapid increase in intensity. In the areas near the coast and central North Carolina where the most rain fell on 2 and 4 September 1996, the high surface moisture may have caused more surface evaporation, which would cool the surface and reduce the sensible heat flux in these locations. The area between these locations where the cell intensified, the minimum in surface moisture may have caused an area of lower surface evaporational cooling, resulting in an increase of surface sensible heat flux. These results are consistent with those of Tuleya (1994) in that surface temperature seemed to have a greater effect on the intensity of the storm after landfall than surface moisture. As the convective cell in Hurricane Fran moved to the northwest away from the area of minimum precipitation and into the area of maximum precipitation, the cell weakened quickly as it encountered a surface that may have been cooled by evaporation. The rainfall that was produced in central and eastern North Carolina in the days preceding Hurricane Fran also had an impact on the extensive and damaging flooding that occurred throughout the state.

Figure 16b is an objective analysis of precipitation on September 5 and 6, which can be attributed to Hurricane Fran. It can be seen in the figure that the contours of constant precipitation accumulation parallel the coastline from Cape Fear to Jacksonville and the New River Inlet. The accumulated precipitation increased farther inland along the path of Fran with a maximum of precipitation occurring in Sampson and Duplin counties. This precipitation pattern is indicative of an increase in precipitation as Hurricane Fran made landfall at Cape Fear. The area of the greatest increase in precipitation after landfall was in the northeast quadrant of the hurricane where precipitation contours closely parallel the coastline. This is also the region of greatest convergence due to surface friction as counterclockwise winds around the eye are directed to the northwest, perpendicular to the coast. The low-level divergence at the time of landfall was calculated using Eta model initialization data and is shown in Figure 17. The area of strongest convergence is to the northeast of the eyewall where the counterclockwise winds are directed perpendicular to the coastline. This shows that the temporary increase in rainfall was a result of enhanced low-level convergence by increased surface friction. This conclusion is consistent with the results of the studies by Powell (1987) and Tuleya and Kurihara (1978). Figure 18 shows the evolution of low-level moisture convergence from 0000 UTC 6 September to 0600 UTC 6 September 1996. It can be seen in the figure that the moisture convergence increased as the storm made landfall. This can be attributed to the increase in surface friction, which increased the ratio of the radial wind component to the tangential wind component. Heavy rainfall over North Carolina and Virginia in the days preceding Fran provided high surface moisture which helped to moisten the boundary layer. As Fran made landfall, the synoptic-scale moisture was brought into the center of the storm by the increased inflow toward low pressure. The figure also shows that the area of maximum moisture convergence was located directly in the path of Fran. The convergence of moisture ahead of the storm aided the development of the convective cell after landfall and helped maintain the cell as it moved into Virginia. In addition to the angle of the primary circulation of Fran with respect to the coastline, the wind speed also contributed to the enhancement of low-level convergence. A surface wind analysis by the Hurricane Research Division (HRD) revealed that a radial wind maximum was located to the northeast of the eyewall (Figure 19). The presence of the wind maximum and its orientation to the coastline made the region to the northeast of the eyewall a preferred location for low-level convergence, which led to increased convection and precipitation. The point at which the wind maximum intersects the coastline at a perpendicular angle is also the point at which increased convection is initiated. Radar images around the time of landfall show that convection is increasing to the northeast of the eyewall.

A second feature to note in the precipitation analysis (Figure 16b) is the existence of a second precipitation maximum in the area of Wake County. This maximum in precipitation provides surface-based evidence for the presence of the intense convective cell that formed as the remnants of the eyewall of Fran entered Johnston County. The cell intensified and organized into a bow echo-type feature, producing copious amounts of rain in the Triangle area. Though filtered out of the objective analysis, some stations in the Raleigh area reported nearly nine inches of rainfall from Hurricane Fran. The large rainfall amounts from Fran combined with rainfall totals of several inches produced by a storm two days earlier caused extensive flooding in central and eastern North Carolina.

3) Dry air intrusion and rear inflow jet

Radar images of Fran at landfall (Figure 8) show that the storm began to take on an increasingly asymmetric structure as it approached land. This asymmetric structure was caused by the advection of dry air into the southern side of the storm. Figure 20 is an analysis of dewpoint temperature at 500mb at the time that Fran made landfall from Eta model initialization data. The mean wind direction in the region was from the south; as a result, the dry air was being advected into the south side of Fran. As Fran moved farther inland, the advection of dry air began to occur at lower levels. The 850mb moisture advection was computed at 0600 UTC and is shown in Figure 21. The figure shows that dry air was being strongly advected into the southern and eastern portions of the storm at 850mb. Satellite images taken a few hours after landfall show that the southeastern portion of the storm has been completely eroded away by the dry air from the south, which became entrained into the counterclockwise circulation of the storm.

Studies dealing with bow echoes and downbursts emphasize the importance of a rear inflow jet that advects dry air into the back of a convective cell and provides high momentum air that is transported to the surface (Caracena and Maier 1987, Lee et al. 1992, Johns and Hirt 1987). The dry air intrusion behind Fran may provide evidence of the rear inflow jet. Data from the initialization runs of the Eta model were analyzed and used to compute various fields. Figure 22 is an analysis of the radial wind computed at 850mb. It is evident from the figure that there is a strong inflow of air toward the center of Fran from the south, providing evidence of a rear inflow jet. Moisture analyses have shown a region of dry air to the south of Fran. The dry air to the south may have been advected into the circulation of the storm by the rear inflow jet. It should also be noted in the figure that strong radial convergence is occurring at the center of Fran, which contributed to the intensification of the convective cell.

4) Analysis of the Sounding Data and the Storm Environment

a) Evidence of the dry intrusion and rear inflow jet

Rawinsonde data was collected from Newport, North Carolina, which is located approximately 145 kilometers to the northeast of where Fran made landfall. Vertical soundings taken at 2300 UTC 5 September (Figure 23a) and 0500 UTC 6 September (Figure 23b) were used in the analysis. The sounding at 2300 UTC was taken as Fran made landfall, and the sounding at 0500 UTC was taken after landfall when it had an asymmetric structure. In both soundings, a wind maximum of 50 ms^{-1} is present just below 700mb. Soundings at both times also show a layer of dry air between 900mb and 700mb. The dry intrusion is especially pronounced at 900mb in the 0500 UTC sounding, which was taken after Fran made landfall. Additional drying at lower levels may have been caused by the descent of the inflow jet and the subsequent warming by subsidence. The analysis of sounding data provides observational evidence of a descending rear inflow jet that aided the organization of the convection into a bow echo after landfall. The production of strong downbursts can also be attributed to the rear inflow jet, which brought dry air into the mid-levels of the storm. The mid-level dry layer caused evaporative cooling, which increased the density of air at that level, adding to the intensity of the outflow from the cell.

b) Stability and the storm environment

The rawinsonde data from Newport was also used to calculate stability parameters and determine if the environment of Hurricane Fran was favorable for the formation of a bow echo. The favored environmental parameters for bow echo formation are convective instability, low relative humidity in the mid-troposphere, and strong winds in the lower to mid-troposphere. The bulk Richardson number (BRN), which is the ratio of buoyancy to vertical shear, is typically low in the bow echo environment due to strong vertical shear and low CAPE. In Hurricane Fran, several of these necessary parameters were present as the storm made landfall.

The buoyancy of the environment, which is measured by CAPE, was low in Fran, which is typical of a hurricane environment because the lapse rate is usually near moist adiabatic through most of the troposphere. The CAPE was highest in the 2300 UTC sounding (613 J kg $^{-1}$) due to conditional instability below 600mb, while the 0500 UTC temperature profile was moist adiabatic or greater nearly throughout the entire sounding. In the composite temperature profile of tornadic hurricanes in McCaul (1991), the temperature profile was very similar to the 2300 UTC sounding, with a conditionally unstable layer below 600mb. The low CAPE and strong low level shear resulted in a bulk Richardson number (BRN) that was low (8). The shear was calculated using the average wind velocities in the lowest 6000m layer. The sounding at 0500 UTC showed a wind speed maximum at 700mb, which is the rear inflow jet. Below this level there was unidirectional shear of 35 ms^{-1}, which is typical of a hurricane environment (McCaul and Weisman 1996). In the study by McCaul and Weisman (1996), the simulated hurricane supercell had CAPE (618 J kg $^{-1}$) and BRN (8) values that were nearly identical to the values that were computed in the 2300 UTC sounding in Fran. The sounding used in the simulation displayed the typical thermal profile of the inflow region of a tropical cyclone. These characteristics include a moist adiabatic lapse rate, high relative humidity throughout the troposphere, and little or no capping inversion. Table 1 is a comparison of the characteristics of environmental soundings in Hurricane Fran and in the midwest supercell and hurricane supercell used in the study by McCaul and Weisman (1996).

The values of the stability parameters that were calculated in Hurricane Fran are typical of a hurricane environment and therefore cannot exclusively explain the formation of the bow echo in Fran. Similar to the composite sounding of McCaul (1991), the lapse rate was moist adiabatic, there was little capping inversion, and the CAPE and BRN were low. The element that was present in Fran that seems to have been responsible for the formation of the bow echo was the rear inflow jet that provided dry air and strong winds in the lower troposphere. Dewpoint depressions in the composite sounding by McCaul (1991) were generally less than 6ºC, while maximum dewpoint depressions in Fran were 7ºC at 2300 UTC to 20ºC at 0500 UTC. In a typical hurricane sounding, the relative humidity is high throughout the lower and mid-levels of the troposphere. In the soundings taken during Hurricane Fran, a distinct dry layer was present between 900mb and 700mb. It seems to have been caused by the rear inflow jet, which brought in dry air from the south and additionally dried the air through subsidence as the inflow jet descended. This may have been the key ingredient that organized the convection into a bow echo and produced strong downbursts.

Storm-relative helicity was computed using a hodograph algorithm in WATADS 9.0. Storm-relative helicity can be described as the component of the horizontal vorticity in the direction of the storm-relative flow. Higher values of helicity indicate a higher likelihood of tornado formation. The direction of the cell was approximately toward 315º at $8 ms^{-1}$. Values of storm-relative helicity from 0 to 3 km were around $106 m^2 s^{-2}$.

McCaul and Weisman (1996) computed storm-relative helicity values of 149m^2s^{-2} for their simulated hurricane supercell. The lower values of storm-relative helicity may help to explain the absence of mesocyclones in the convective cell in Hurricane Fran. A comparison of storm-relative helicity between a midwest supercell sounding, a modified hurricane supercell sounding, and a sounding taken as Hurricane Fran made landfall is shown in Table 1.

Variable	Oklahoma supercell	Hurricane supercell	Hurricane Fran convective cell
Storm motion (u/v; ms^{-1})	4.3/14.7	-2.8/15.2	-5.6/5.6
CAPE (J kg^{-1})	2620	619	613
0-3 km helicity	154	149	106
Bulk Richardson number	35	8	8

Table 1. Characteristics of environmental soundings from an Oklahoma supercell event at 2100 UTC 20 May 1977, a modified composite sounding from Hurricane Danny (1985), and from Newport, NC at 2300 UTC 5 September 1996 during Hurricane Fran. Oklahoma supercell data and modified hurricane supercell data from McCaul and Weisman (1996). The hurricane supercell sounding was modified by McCaul and Weisman (1996) to offset unrealistically low humidity measurements.

IV. Comparisons Between Hurricanes Opal and Fran

This thesis has investigated the intensity and structural changes in two landfalling hurricanes, Hurricane Opal and Hurricane Fran. Differences and similarities in the processes that caused the changes can be drawn between the two storms. The most apparent similarity is the presence of an intrusion of dry air that resulted in each storm taking an asymmetric structure shortly before landfall. The effect of the dry intrusion on Hurricane Opal was, along with other processes, to aid in a rapid decrease in the intensity of the storm before landfall. Dry air on the western side of Opal at middle and upper levels created an asymmetric storm structure and reduced the amount of diabatic heating in the storm, resulting in a decrease in the central pressure. In Hurricane Fran, an intrusion of dry air from the south also caused an asymmetric storm structure and may have contributed to a slight decrease in central pressure before landfall. However, the dry air intrusion in Fran also contributed to the organization of convection into a bow echo after landfall. The dry rear inflow jet entered the storm at middle to lower levels of the atmosphere and descended, enhancing surface convergence. This process did not occur in Hurricane Opal. One explanation for this difference is that the dry air intrusion into the western side of Opal occurred at middle to upper levels. The source of this dry air was a synoptic-scale upper level trough, and possibly subsidence on the cyclonic side of the outflow jet. At low-levels, Opal was still to the east of an approaching cold front. At upper levels, the dry air had advanced ahead of the surface front and was advected into the western side of Opal. In Hurricane Fran, the dry air was at middle to lower levels and was advected around the south side of the storm by the counter-clockwise circulation. Since the dry air was located at the same level as the rear inflow jet, the dry air was brought into the center of the storm. This enhanced the surface convergence and aided in the organization of the convection into a bow echo.

The major difference between the two storms in this study is that a synoptic upper level trough strongly affected Hurricane Opal, while Hurricane Fran experienced very little synoptic trough interaction. The upper level trough had a strong influence on the structure and intensity of Hurricane Opal through numerous processes, including eddy momentum flux convergence, upper level divergence, potential vorticity interaction, and vertical shear. These processes did not have an important effect on Hurricane Fran because a synoptic upper level trough was not present at the time that Fran made landfall. Despite the absence of any significant synoptic scale interaction, there were several mesoscale processes that occurred with Fran, such as a dry air intrusion, sensible heat flux gradients, a rear inflow jet, and surface convergence due to friction. The effect of these processes was to change the structure and intensity of Fran on a local scale within the storm by enhancing and organizing convection within the storm.

V. Conclusions

The purpose of this thesis has been to investigate the processes that affect the structure and intensity of landfalling hurricanes. This has been accomplished by studying Hurricane Opal and Hurricane Fran. Hurricane Opal has been used as a case study of how trough interaction processes can affect the intensity and structure of a tropical cyclone. Previous studies that dealt with trough interaction with hurricanes were reviewed, and the effect of upper level troughs on tropical cyclones was discussed. As Hurricane Opal approached the Gulf Coast of the United States, it seems to have been strongly influenced by an upper level trough over the central United States. Initially, the effect of the trough may have been to aid in the rapid intensification of Opal in conjunction with a warm core eddy in the Gulf of Mexico. The trough interaction processes that area suspected to have aided the intensification were eddy momentum flux convergence and increased upper level divergence. As Opal moved closer to the trough, the positive trough interaction processes were offset by the negative processes of vertical shear, PV displacement, and a dry air intrusion. This led to a change in the convective structure of the storm and a decrease in the central pressure of Opal shortly before landfall.

Numerous studies on Hurricane Opal are currently being conducted. Hurricane Opal is an excellent case study to use for research on trough interaction processes, air-sea interaction with hurricanes, and the effect of storm structure on intensity changes in hurricanes. Future studies will have to take a more quantitative approach in the analysis of trough interaction processes. The distinction between positive and negative trough interaction processes must be further clarified, since the same processes that can strengthen a tropical cyclone can also weaken it. The parameters that determine this difference must be determined in order to improve forecasts of tropical cyclone intensification.

Hurricane Fran was used in this study as an example of how the structure and local intensity changes in a hurricane can be influenced after landfall without the aid of an upper level trough. The initiation of intense convection after landfall was investigated in Hurricane Fran. The mechanisms of formation and organization of the convection were investigated, and characteristics of severe storms that form in hurricanes were discussed and compared to severe storms that form in the Central United States. Initial investigations into the causes for the formation of an intense convective cell in Hurricane Fran suggest that the cell was initiated by enhanced low level convergence created by increased surface friction after landfall. The surface friction caused the primary circulation to increase its cross-isobar angle. This increased the ratio of radial wind to tangential wind, causing a greater percentage of the total flow to be directed toward radial convergence. The increased boundary layer inflow toward low pressure increased mass convergence, which enhanced rising motions. Radar observations show that the convection to the northeast side of the remaining eyewall was increased shortly after landfall. Analysis of surface precipitation data also shows that rainfall increased after Fran made landfall. A wind maximum located to the northeast of the eyewall was oriented perpendicular to the coastline, which created a region of maximum surface convergence due to friction. Heavy precipitation in the days before Fran made landfall provided sensible heat fluxes gradients, which helped to initiate convection after landfall. The high surface moisture also provided synoptic-scale moisture in the boundary layer, which enhanced moisture convergence ahead of the storm and helped to maintain the convection several hours after landfall.

Previous studies have shown that the enhancement of convection after landfall is not an uncommon occurrence (Willoughby and Black 1996). For example, Hurricane Andrew experienced an increase in convection after making landfall in Florida. However, the organization of a convective cell in a hurricane into a bow echo-type structure as in Hurricane Fran seems to be a rare occurrence, since research into the phenomenon has been virtually nonexistent. A significant difference between the cell in Hurricane Fran and the convection in Hurricane Andrew is that the cell in Fran evolved into a bow echo while the convection in Andrew maintained a cellular structure (Willoughby and Black 1996). The intensity of the convection in Fran was also maintained much farther inland than the convection in Andrew, despite the fact that Andrew was a much stronger hurricane than Fran. A possible explanation for these differences is the intrusion of dry air into the south side of Fran by a rear inflow jet. Andrew maintained a fairly symmetric cloud structure after making landfall, while Fran became very asymmetric. The dry intrusion and rear inflow jet seem to have played a critical role in the organization of convection into a bow echo. Previous studies have shown that a rear inflow jet and a vorticity couplet are important mechanisms in bow echo formation. Sounding data and model data analyses have provided evidence for the presence of an inflow of dry air from the south into Fran in the lower to mid-troposphere. The rear inflow jet seems to have advected dry air into the storm and eroded the cell by subsidence and evaporation.

The evaporation and subsidence caused by the rear inflow jet also contributed to the organization of the convective cell into a bow echo and the production of strong downbursts that resulted in the extensive damage in the Raleigh area. The inflow of dry air into the cell caused significant evaporative cooling at mid-levels. The cool, dense air combined with the high momentum transfer from the rear inflow jet may have resulted in the downbursts that produced strong straight-line winds similar to a derecho. According to Johns and Hirt (1987), the development of a derecho is aided by strong winds and low humidity in the mid-troposphere. Observations show that these conditions were met in Hurricane Fran. Caracena and Maier (1987) stated that storms with heavier rain rates might not require an elevated dry layer to produce a microburst due to increased water loading. While the mid-tropospheric level of Fran may not have been as dry as that of microburst-producing storms in the midwest U.S., the large rain rates in Fran may have compensated for this discrepancy.

This study into the structure of Hurricane Fran provides several opportunities for additional research. A modeling study that tests the sensitivity of convection in landfalling hurricanes to soil moisture gradients, inflow strength, a mid-level dry layer, radial inflow strength, moisture convergence, storm alignment to the coastline, and storm asymmetry would determine which of these processes are most important in initiating and maintaining the convection. A study that investigated the structure of numerous landfalling hurricanes would help to find the frequency of convection initiated after landfall and the pattern into which it is most often organized. Such studies would have many benefits to an operational forecaster. The current study can provide forecasters with certain guidelines in predicting local convective intensification in landfalling hurricanes. Forecasters should be aware of large heat flux gradients produced by differences in soil moisture that can generate local circulation. The presence of a secondary wind maximum away from the eyewall and its orientation to the coastline can alert forecasters to the possibility of strong low level convergence that can initiate convection and the area in which it is most likely to occur. Forecasters should also know if regions of dry air are located near a hurricane that may be advected into the circulation and affect its structure and intensity. Parameters such as storm-relative helicity and CAPE can be used by operational forecasters to determine if the hurricane environment will be favorable for tornado development.

VI. References

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Appendix A. A history of hurricanes in North Carolina

North Carolina has a history of receiving significant damage from hurricanes. Ever since the first expeditions to Roanoke Island in 1586, hurricanes are recorded to have caused tremendous damage to the state. The state's protruding coastline makes it a favorable target for tropical cyclones that recurve northward in the western Atlantic Ocean. Not surprisingly, the most favored location for tropical cyclones to make landfall in North Carolina is Cape Hatteras. The other two protrusions in the North Carolina coastline, Cape Fear and Cape Lookout, are also favored areas for tropical cyclones to make landfall. Table A1 lists all hurricanes and tropical storms that have made direct landfall in North Carolina since 1800.

Approximate date of landfall	Storm name, intensity at landfall	Approximate location of landfall	Estimated wind speed (kt)
9/28/1806	NA	Ocracoke Inlet	
9/3/1815	NA	Wilmington	
9/2/1821	NA	Cape Lookout	
6/3/1825	NA	Morehead	
8/24/1827	NA	Cape Hatteras	
9/4/1834	NA	NC/SC border	
8/18/1837	NA	Cape Fear	
7/12/1842	NA	Portsmouth	
8/24/1842	NA	Ocracoke	
9/7/1846	NA	Hatteras	
9/4/1856	NA	Wrightsville Beach	
9/9/1857	NA	Hatteras	
8/19/1871	NA	Southport	
9/28/1874	TS	Southport	60
11/10/1875	NA	Long Beach	

9/17/1876	TS	NC/SC border	60
10/23/1878	2	Morehead City	85
9/11/1883	1	Southport	80
10/22/1893	TS	West of Hatteras	50
10/26/1897	TS	North of Hatteras	55
8/16/1899	3	Hatteras	95
10/31/1899	1	Wrightsville Beach	80
7/11/1901	1	Hatteras	65
7/31/1908	2	Morehead	85
9/3/1913	1	Hatteras	70
9/6/1916	TS	Southport	35
8/25/1918	TS	Morehead	50
9/22/1920	1	Topsail Beach	65
8/23/1933	2	Hatteras	85
9/16/1933	2	Ocracoke	90
9/18/1936	2	Hatteras	85
8/1/1944	1	Southport	80
8/13/1953	Barbara, 2	Cape Lookout	90
8/30/1954	Carol, 2	Hatteras	85
10/15/1954	Hazel, 4	NC/SC border	115
8/12/1955	Connie, 1	Cape Lookout	70
8/17/1955	Diane, 1	Carolina Beach	75
9/19/1955	Ione, 2	Salter Path	90
9/11/1960	Donna, 2	East of Wilmington	95
8/27/1971	Doria, TS	Atlantic Beach	55
9/30/1971	Ginger, 1	Atlantic Beach	65
9/9/1984	Diana, 1	Long Beach	80
9/26/1985	Gloria, 2	Hatteras	90
6/20/1996	Arthur, TS	Morehead	35
7/13/1996	Bertha, 2	Topsail Beach	90
9/6/1996	Fran, 3	Cape Fear	100

Table A1. List of all hurricanes and tropical storms that have made direct landfall in North Carolina since 1800. Approximate location of landfall and estimated wind speed at landfall are also listed. Data compiled from the Colorado State Tropical Cyclone database.

Reliable classification of the intensity of tropical cyclones began in 1886. Since that time, there have been 951 tropical cyclones that have been recorded in the Atlantic

Ocean and the Gulf of Mexico. Approximately 166 or 17.5% of those tropical cyclones passed within 300 miles of North Carolina. Table A2 contains the number and percentage of tropical storms and hurricanes that made landfall in North Carolina or made landfall in another state and later passed through North Carolina. The coast of North Carolina can expect to receive a tropical storm or a hurricane once every four years, while a tropical cyclone has an impact somewhere in the state every 1.3 years.

	Direct landfalling TCs in NC	TCs that passed through NC (made landfall in another state)
Number of	28	82
Percentage of	2.9	8.6
Years per TC (period)	4	1.3
TCs per year (frequency)	.25	.74

Table A2. Number and percentage of hurricanes and tropical storms to make direct landfall in North Carolina since 1886. Number of years between storms and number of storms per year is also given. Data compiled from the Colorado State University Tropical Cyclone database.

1996 was a rare year in the hurricane history of North Carolina. Tropical Storm Arthur, Hurricane Bertha, and Hurricane Fran all made direct landfall on the North Carolina coastline. It was the most active tropical cyclone season in the state since 1955, when Hurricanes Connie, Diane, and Ione all hit the coast. 1953, 1954, and 1955 was the most active three-year period of tropical cyclones in the state's history. Over that period, six hurricanes made direct landfall in North Carolina. The most powerful hurricane to hit the state made landfall in 1954, Hurricane Hazel. It was the only category 4 hurricane to make landfall in North Carolina. 1996 saw the most costly hurricane to ever hit North Carolina, Hurricane Fran. The landfall location of Fran near the city of Wilmington and its progression into the Raleigh-Durham area caused an estimated $2.5 billion in damage in North Carolina alone.